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THE EFFECTS OF SCREEN SLOT SIZE,  
SCREEN DIAMETER,  
AND THROUGH-SLOT VELOCITY  
ON ENTRAINMENT OF ESTUARINE  
ICHTHYOPLANKTON THROUGH  
WEDGE-WIRE SCREENS

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STEPHEN B. WEISBERG

WILLIAM H. BURTON

ERIC A. ROSS

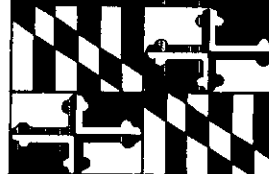
FRED JACOBS

MARTIN MARIETTA ENVIRONMENTAL SYSTEMS  
9200 RUMSEY ROAD  
COLUMBIA, MARYLAND 21045

PREPARED FOR:

MARYLAND POWER PLANT SITING PROGRAM

DEPARTMENT OF NATURAL RESOURCES ■ DEPARTMENT OF HEALTH AND MENTAL  
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MENT OF AGRICULTURE ■ PUBLIC SERVICE COMMISSION



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Prepared by:

Stephen B. Weisberg  
William H. Burton  
Eric A. Ross  
Fred Jacobs

Martin Marietta Environmental Systems  
9200 Rumsey Road  
Columbia, Maryland 21045

Prepared for:

Maryland Department of Natural Resources  
Power Plant Siting Program  
Tawes State Office Building  
Annapolis, Maryland 21401

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FOREWORD

This final report, "The effects of screen slot size, screen diameter, and through-slot velocity on entrainment of estuarine ichthyoplankton through wedge-wire screens," was prepared by Stephen B. Weisberg, William H. Burton, Eric A. Ross, and Fred Jacobs of Martin Marietta Environmental Systems for Dr. Paul Miller of the State of Maryland Power Plant Siting Program. The study was conducted from August 1982 to July 1983 as part of a program to test alternative intake screening devices in the State of Maryland. The work was conducted in its entirety by Martin Marietta Environmental Systems under Contract Numbers Pl-83-02 and Pl-84-02.

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# ABSTRACT

Tests were conducted in the Patuxent estuary from August 1982 to July 1983 to determine how certain design characteristics of wedge-wire screens affect entrainment of ichthyoplankton through the screens. The study examined the effect of a) altering screen slot size (1mm, 2mm, and 3mm screens) while maintaining a constant through-slot velocity (20 cm/sec), b) altering through-slot velocity (9.5 cm/sec, 20 cm/sec and 40 cm/sec) while maintaining a constant screen slot size (2 mm), and c) altering screen diameter while maintaining constant through-slot velocity (~20 cm/sec) and constant slot size (2mm). Size specific responses of two species, bay anchovy (Anchoa mitchilli) and naked goby (Gobiosoma boscii), were examined.

In comparison with an open port, screens of all slot sizes reduced entrainment, the effect being highly dependent on fish size. Entrainment through a 1-mm screen was reduced for both species when fish reached 5 mm in length. For smaller fish, neither species was excluded by screens. Virtually total exclusion by 1-mm screens occurred for both species when fish were greater than 10 mm in length. Evidence for two mechanisms of exclusion, physical exclusion and escape by fish from quickly dissipated flow fields, were apparent.

Screen slot size had a measurable, but small, effect on the number of fish entrained. For small fish, no effect related to slot size was found. For large fish, the effect of slot size was the difference between total exclusion produced by the physical barrier of a 1-mm screen, and an ~ 80% reduction in entrainment found with screens of larger slot size. For fish of intermediate size, the difference in exclusion efficiency between a 1-mm and 3-mm screen was approximately 25%.

The effect of altering through-slot velocity over a four-fold range was found to be significant for naked gobies, but not for bay anchovies. Higher through-slot velocity resulted in greater rates of entrainment for naked gobies. For small gobies, this was apparent over the whole range of through-slot velocities tested. For larger gobies, only the highest through-slot velocity increased entrainment. It is suggested that species such as naked gobies, which inhabit areas near the screen, will be more affected by these changes in flow than will open water species, such as anchovies, which typically remain outside the influence of the withdrawal field.

The effect of screen diameter was found not to be very important, particularly for larger fish. For small individuals, a reduction of the screen diameter was accompanied by a slight reduction in entrainment.

## I. INTRODUCTION

The loss of biota by impingement and entrainment is a potentially major impact which large volume water users can have on aquatic communities. In an effort to reduce such impacts, much research has been conducted to identify cost-effective and ecologically sound water-intake modifications (American Society of Civil Engineers, 1982). One promising technology designed to eliminate impingement and reduce entrainment is the cylindrical wedge-wire screen (also referred to as profile wire screens, or Johnson screens).

Wedge-wire screens are a passive system, designed to reduce entrainment by physical exclusion and by exploiting hydrodynamics. Physical exclusion occurs when the mesh size of the screen (e.g., 1 mm) is smaller than the organism susceptible to entrainment. Hydrodynamic exclusion results from maintenance of a low through-slot velocity which, because of the screen's cylindrical configuration (Fig. I-1), is quickly dissipated, thereby allowing organisms to escape the flow field. When located where ambient water velocity across the screen exceeds velocity through the screen, their effectiveness in reducing impingement and entrainment is enhanced (Hanson et al., 1978).

In situ observations have shown that impingement is virtually eliminated when wedge-wire screens are used (Hanson et al., 1978; Lifton, 1979; Browne et al., 1981). Furthermore, laboratory studies (Hanson, 1981; Heuer and Tomljanovich, 1978) and field studies (Zeitoun et al., 1981; Lifton, 1979; Browne et al., 1981; Delmarva Power and Light, 1982; Weisberg et al., 1983), have shown that fine mesh wedge-wire screens also reduce entrainment.

Despite the apparent success of wedge-wire screens in reducing entrainment, there has been no attempt to distinguish the relative importance of low through-slot velocity and small slot width on exclusion. Although some studies have examined the effect of varying screen slot size (Browne et al., 1981; Zeitoun et al., 1981; Lifton, 1979), and others have examined the effect of altering the hydrodynamic field under laboratory conditions, (Hanson, et al., 1978), no study has partitioned these two factors under field conditions. Further, it can be assumed that the effectiveness of both mechanisms for exclusion are influenced by fish size, but only Delmarva Power and Light (1982) has examined the effect of fish size in relation to either mechanism of entrainment reduction. If wedge-wire screens are to be used for entrainment reduction, then an understanding of these mechanisms would seem to be a necessary condition for choosing an optimal deployment strategy.

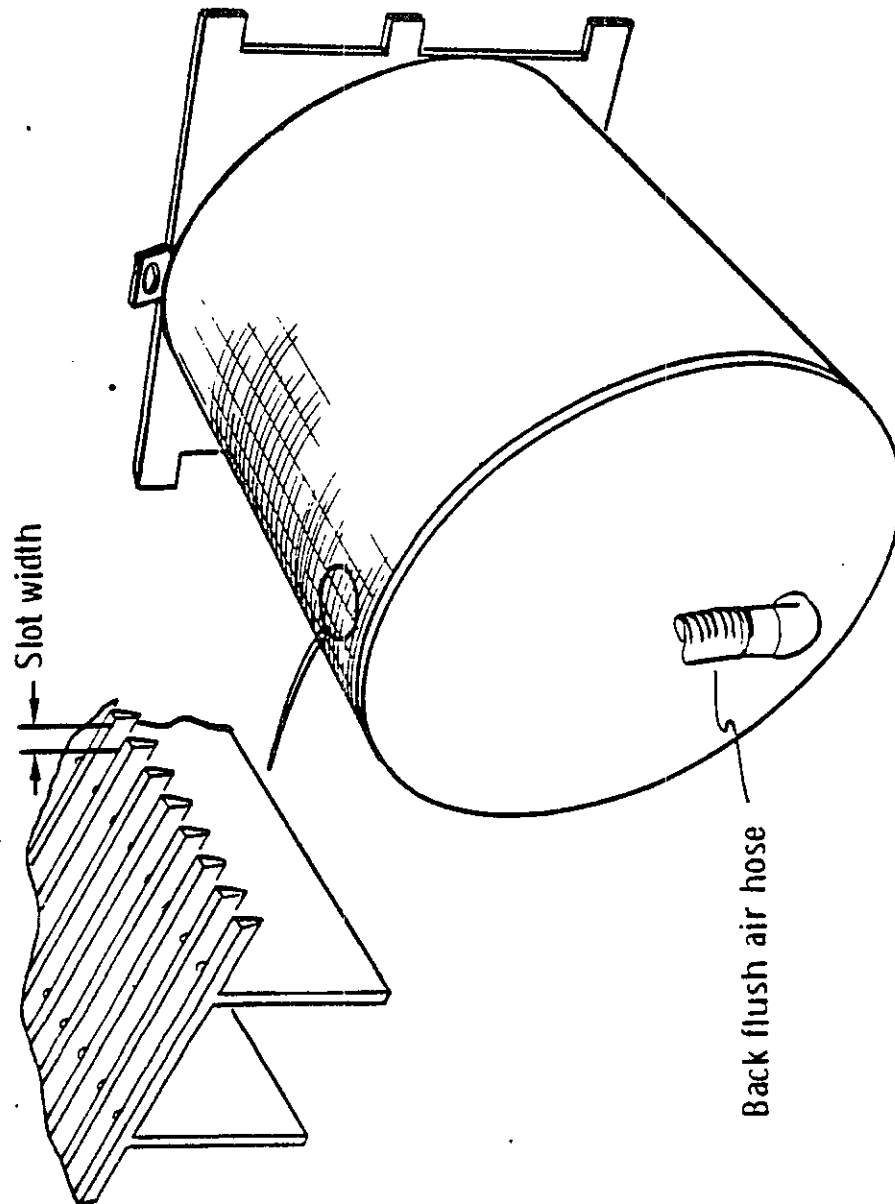


Figure I-1. Schematic of a bulkhead-mounted screen, with cutaway of wedge-wire configuration

In this study, collections were made under field conditions to determine:

- The effect of screen slot width on entrainment rate when through-slot velocity is held constant.
- The effect of through-slot velocity on entrainment rate when slot-width size is held constant.
- The effect of screen surface area on entrainment rate when both slot-width size and through-slot velocity are held constant.
- The influence of these factors on different size groups of two common estuarine ichthyoplankton species.

## II. METHODS

### A. STUDY SITE

Tests were conducted at the Chalk Point Steam Electric Station, located on the Patuxent River in Southeastern Prince Georges County, Maryland (Fig. II-1). The test device was moored midchannel in the Chalk Point intake canal approximately 25 m downstream from the mouth (Fig. II-2). The intake canal is 62 m long, 25 m wide, and about 3 m deep, and draws its water from the Patuxent River via a canal dredged through Swanson Creek. During the tests, a unidirectional current of about 15 cm/sec was maintained in the canal by the operation of the power plant.

#### Test Facility

The model intake test facility used in this study was a 7.0-m x 5.2-m barge (Fig. II-3) equipped with two identical 25-horsepower turbine pumps that could be operated at two speeds. In 1982, each pump had a capacity of approximately 7.7 m<sup>3</sup>/min at high speed and 3.7 m<sup>3</sup>/min at low speed. Refurbishment of the pumps, prior to 1983 studies, increased withdrawal rate to 12 m<sup>3</sup>/min at high speed and 5.5 m<sup>3</sup>/min at low speed. Intake orifices were 2-m apart, 35 cm in diameter and 1-m below the water surface. Water exited from the barge through identical 25-cm diameter pipes associated with each pump. The barge was situated in the canal so that one port was upstream of the other and the axis of the screens was perpendicular to the current. The upstream port and the downstream port are referred to as the left and right ports, respectively.

#### Screens

Four types of cylindrical screens: 1-mm, 2-mm, and 3-mm screens of nominal diameter, and a 2-mm screen of reduced diameter-were tested. The dimensions of each are shown in Table II-1. Each screen was mounted on backing plates that inserted into vertical tracks to guide the screen over the intake orifices (Fig. I-1). The average velocity through the open slots of the 1-mm, the larger diameter 2-mm, and the 3-mm screens was 20 cm/sec and 9.5 cm/sec for high and low pump speeds, respectively, in 1983. Flow diffusers, intended to equalize flow over the screen surface, were present in all screens.

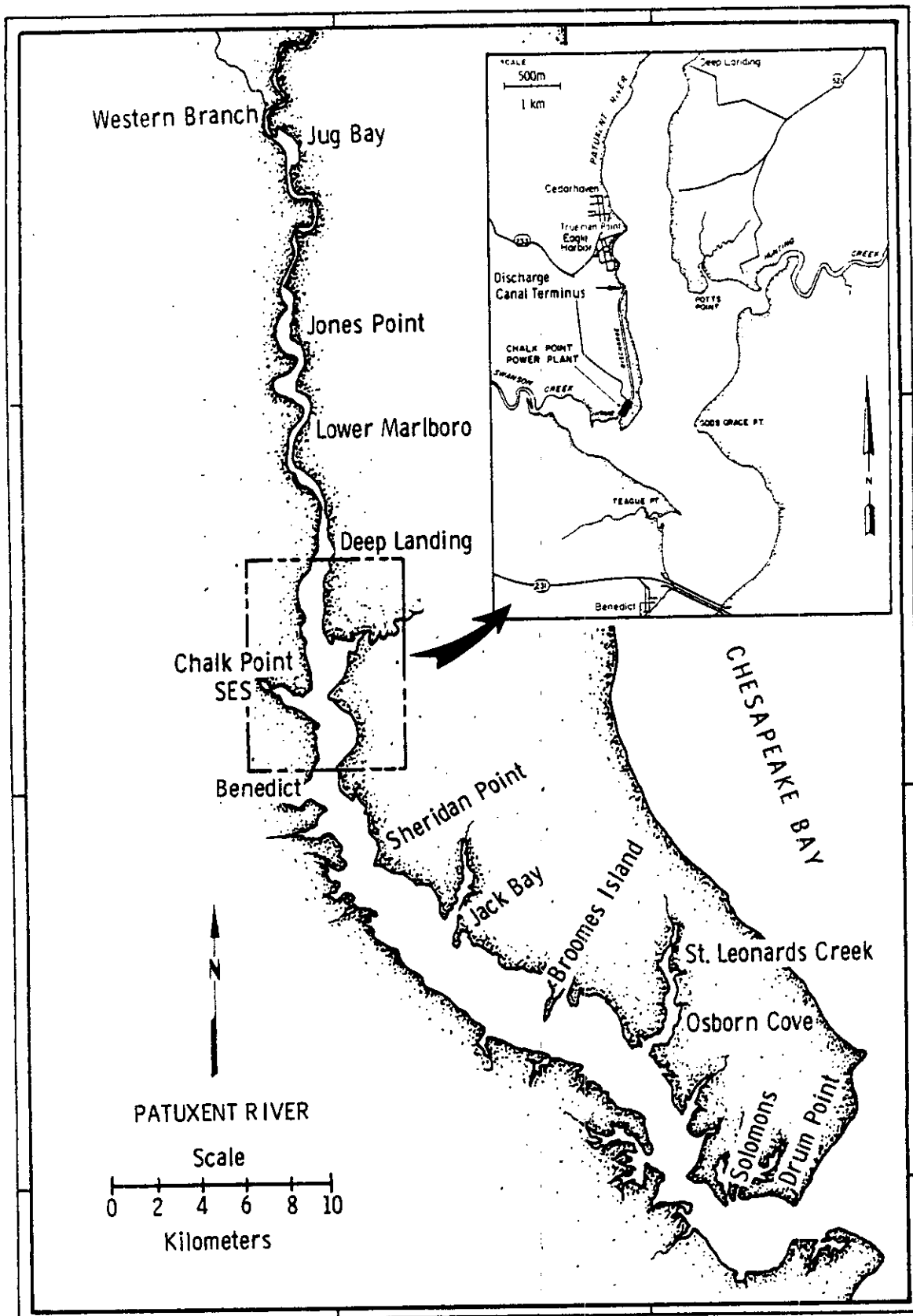


Figure 11-1. Location of Chalk Point Power Plant

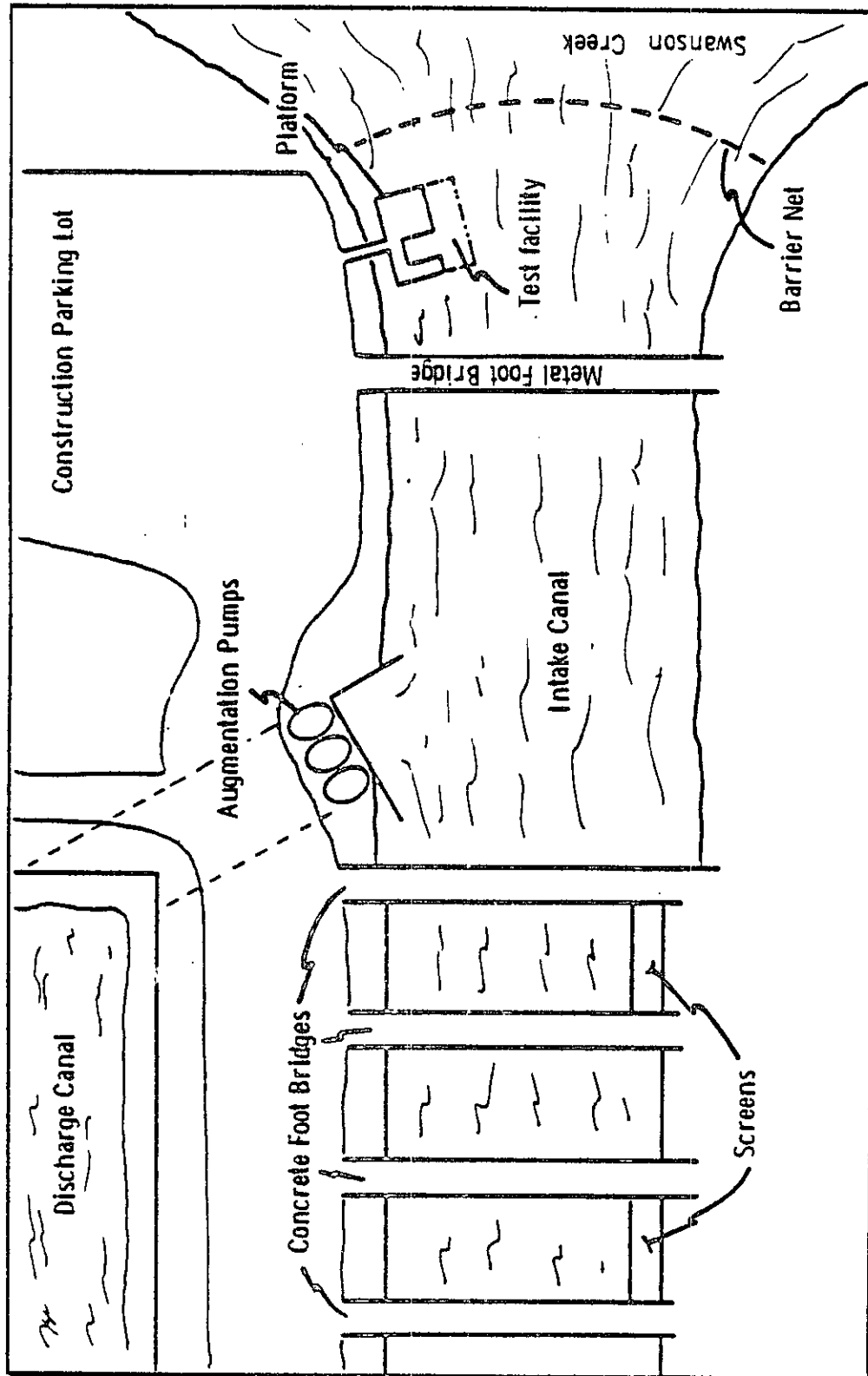


Figure II-2. Location of the test facility in the intake canal

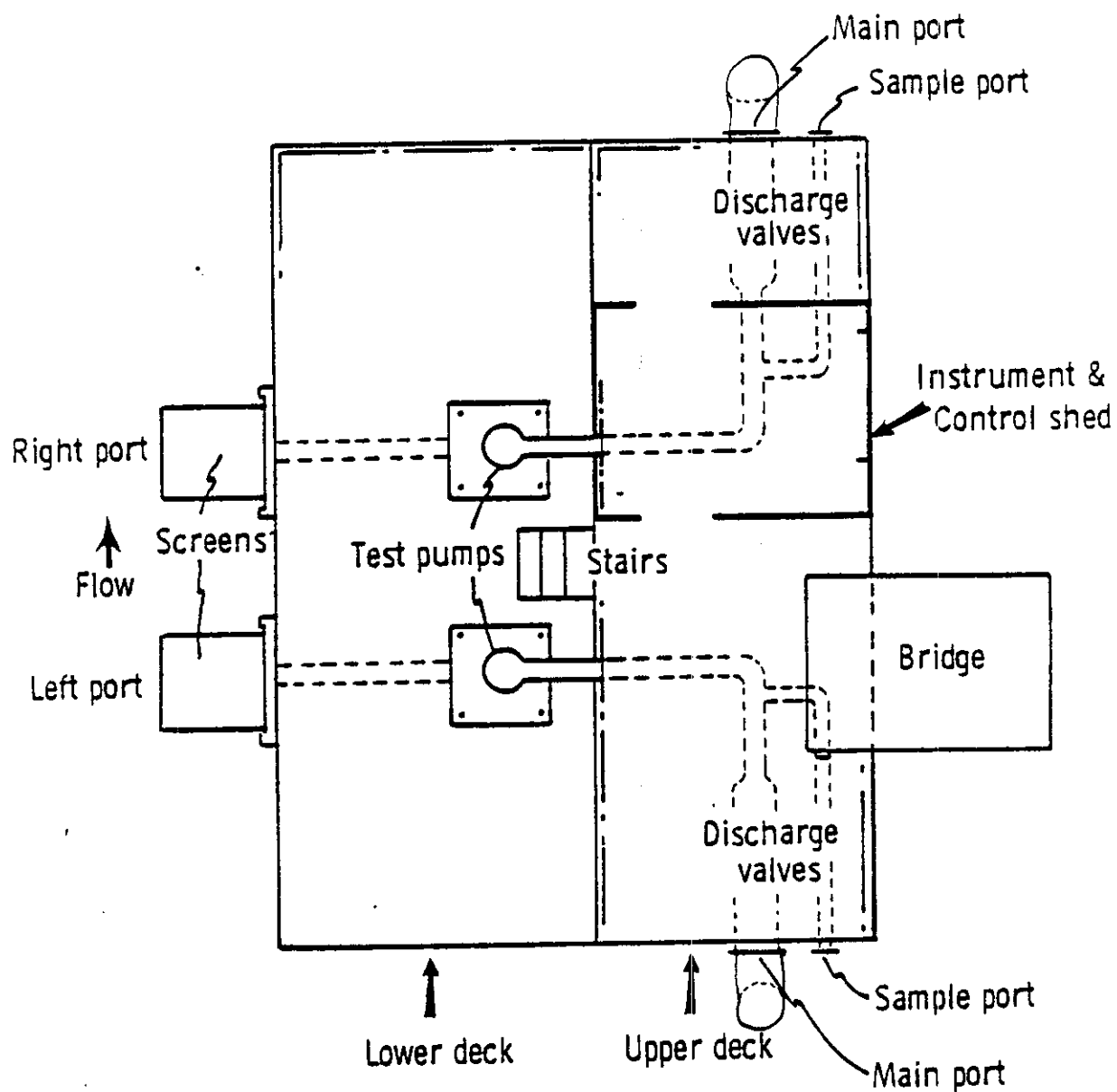


Figure II-3. Schematic of test facility used in this study

Table II-1. Specifications of the types of cylindrical wedge-wire screens tested.

Slot Size (mm)	Screen Diameter (cm)	Length (cm)	Wire Width (mm)	Percent Open Area
1	76	86	2	50
2 (small)	54	46	2	66
2 (large)	76	61	2	66
3	76	55	2	75

## B. SAMPLING SCHEDULE

August 1982

Two samplings were conducted in 1982. All tests were done at night to maximize the number of organisms present and to reduce gear avoidance by visual cues. In tests conducted on 19 August, entrainment through a large diameter 2-mm screen was compared with entrainment through an open port. Six replicate pairs of samples were taken. Each pair consisted of a screened and an unscreened sample. Each condition was tested three times on each port in random order. Towed bongo net samples were taken in the intake canal simultaneously with each sample. In similar tests conducted on 22 August, entrainment through a 1-mm screen was compared with entrainment through an open port. The pumps were run at high speed on both dates.

Summer 1983

Sampling was conducted 11 times (from 12 July to 28 July) in 1983. As in 1982, all samples were collected at night. Seven different treatments (Table II-2) were tested on each port each night. The treatment order was random (the order of test conditions for each night is shown in Appendix A). Towed bongo net samples were taken in the intake canal simultaneously with each sample.

## C. PROCEDURES

Ichthyoplankton entrained through the test facility were collected at the two main exit ports (Fig. II-3) using 505- $\mu$ m mesh plankton nets 1 m in diameter by 4.2 m long. In 1982, approximately 100 m<sup>3</sup> of water was pumped for each collection. In 1983, 360 m<sup>3</sup> and 165 m<sup>3</sup> of water were filtered at high and low pump speeds, respectively.

The stepped oblique bongo tows (0.5 m diameter, 505 $\mu$ m mesh) were taken at the surface and at 1 m and 2 m depths approximately 5-15 m upstream of the test facility.

Table II-2. Treatment possibilities for seven screen size/pump speed combinations tested in 1983.

Screen Type	Pump Speed	Average Through-Screen Velocity (cm/sec)
Open port	High	*
1-mm screen	High	20
2-mm screen (small)	High	40
2-mm screen (small)	Low	19
2-mm screen (large)	High	20
2-mm screen (large)	Low	9.5
3-mm screen	High	20

\* Velocity at the orifice of the open port was 400 cm/sec at high pump speed and 190 cm/sec at low pump speed

Samples from both halves of the bongo nets were combined for processing. Tows took approximately 5 minutes and when combined filtered about 50 m<sup>3</sup> of water. The actual volume of water filtered for each canal sample was calculated using a General Oceanics flowmeter installed in the mouth of one side of the bongo net.

For each sample, salinity, temperature, and dissolved oxygen were measured at the surface and near the bottom of the intake canal. Salinity and temperature were measured with a Beckman salinometer. Dissolved oxygen was measured with a YSI model 57 meter.

All samples were preserved in the field with 5% formalin. In the laboratory, all fishes were sorted by species. Because fin damage precluded measurement of total length, the standard length (SL) of each was recorded to the nearest millimeter. Collections in which eggs were too numerous to count were first sorted for larvae; eggs were then counted by subsampling with a Folsom plankton splitter (McEwen et al., 1954).

#### D. STATISTICAL METHODS

##### Preliminary Analysis

For most analyses in this report, variation in sample density was partitioned using either an analysis of variance (ANOVA) or an analysis of covariance (ANCOVA). A major assumption underlying these linear modeling methods is that homogeneity (equality) of variances exists across different treatment groups. The log transformation [ $\log_e(x+1)$ ] was used for all tests in this report to meet this assumption.

In order to examine size-specific effects of test conditions within species, we analyzed bay anchovy and naked goby data by size category. The categories were selected after determining which size increments would not result in large numbers of empty cells and unequal treatment variances. For bay anchovies, the following size classes were used: <4 mm, 5-7 mm, 8-10 mm, 11-14 mm, and >15 mm. For naked gobies, the following size classes were used: <4 mm, 5-6 mm, 7-8 mm, and >9 mm.

##### Comparison of Entrainment Rates Through Screens of Different Slot Width and an Open Port

For data collected in 1982, the hypothesis that no difference existed in the densities of each size class between ports

(left and right) or under varying screen conditions (open port, 1-mm screen, 2-mm screen) was tested with a two-way analysis of covariance, using canal density as the covariate.

The model used in this analysis was:

$$Y_{ijm} = \mu + \alpha_i + \gamma_j + \gamma_j\beta + (\alpha\gamma)_{ij} + \alpha_i\beta + (\alpha\gamma)_{ij}\beta + \beta (X_{jm} - X) + E_{ijm}$$

where

$Y_{ijm}$  =  $m^{\text{th}}$  ( $m=1, 2\dots 6$ ) observation of pump density taken at the  $i^{\text{th}}$  port ( $i=1, 2$ ), the  $j^{\text{th}}$  screen condition ( $j=1, 2, 3$ )

$\mu$  = overall mean

$\alpha_i$  = effect of the  $i^{\text{th}}$  port

$\gamma_j$  = effect of the  $j^{\text{th}}$  screen condition

$(\alpha\gamma)_{ij}$  = combined effect of the  $i^{\text{th}}$  port and the  $j^{\text{th}}$  screen condition

$\gamma_j\beta$  = combined effect of the  $j^{\text{th}}$  screen condition and canal density

$\alpha_i\beta$  = combined effect of the  $i^{\text{th}}$  port and the canal density

$(\alpha\gamma)_{ij}\beta$  = combined effect of the  $i^{\text{th}}$  port and the  $j^{\text{th}}$  screen condition and canal density

$X_{jm}$  =  $m^{\text{th}}$  observation of bongo net density taken at the same times as the  $j^{\text{th}}$  screen condition

$X$  = overall mean canal density

$\beta$  = pooled regression slope of pump density on canal density

$E_{ijm}$  = error associated with the  $m^{\text{th}}$  pump density observed at the  $i^{\text{th}}$  port and the  $j^{\text{th}}$  screen condition. The errors are assumed normally distributed with common mean 0 and variance  $\sigma^2$ .

For data collected in 1983, the hypothesis that no difference existed in the densities of each size class under varying conditions (open port, 1mm screen, large diameter 2mm screen

at high pump speed, and 3-mm screen) was tested with a blocked one-way analysis of covariance, using canal density as the covariate, and the 22 date-port combinations as blocks.

The model used in this analysis was:

$$Y_{ij} = \mu + \alpha_i + \gamma_j + \gamma_i\beta + \beta (X_{ij} - X) + E_{ij}$$

where

$Y_{ij}$  = observation of pump density taken at the  $i^{\text{th}}$  block ( $i=1, 2 \dots 22$ ), the  $j^{\text{th}}$  screen condition ( $j=1, 2, 3, 4$ )

$\mu$  = overall mean

$\alpha_i$  = effect of block  $i$

$\gamma_j$  = effect of the  $j^{\text{th}}$  screen condition

$\gamma_i \beta$  = combined effect of the  $j^{\text{th}}$  screen condition and the canal density

$X_{ij}$  = observation of net density taken at the  $i^{\text{th}}$  block and the  $j^{\text{th}}$  screen condition

$X$  = overall mean canal density

$\beta$  = pooled regression slope of pump density on canal density

$E_{ij}$  = error associated with pump density observed at the  $i^{\text{th}}$  port and the  $j^{\text{th}}$  screen condition. The errors are assumed normally distributed with common mean 0 and variance  $\sigma^2$ .

When interaction terms were found to be insignificant, they were excluded from the model and a new fit was made that did not include the insignificant terms. When a significant screen-condition effect was found, pairwise comparisons of the adjusted treatment means for the various screen conditions were made (Snedecor and Cochran, 1980).

If the covariate was found to be insignificant (i.e., slope not significantly different from zero) or if interaction terms involving the covariate were found to be significant (implying unequal slopes across treatment groups), ANOVA models, similar to the model above without the covariate terms, replaced the ANCOVA model. If the screen effect was significant in the ANOVA model, Duncan's new multiple range test (Ott, 1977) was used for comparisons among treatments.

Due to the high degree of exclusion caused by screens, or to the low numbers of fish in certain size categories present in the intake canal, Cochran's test for equality of variance showed that in some cases unequal variances across treatment groups remained even after transformation. When the assumption of homogeneity of variance could not be met with transformation, the Friedman rank sum statistic (Conover, 1971) was used. In this test, the observations are ranked within blocks and ranks are then summed over treatments. For the 1982 data, port (left, right) was used as the blocking factor; for 1983, date-port combinations were used. When treatment differences were significant, pairwise comparisons of the treatment mean ranks were made (Conover, 1971). The critical values for each pairwise comparison were determined using a type I error of  $\alpha/2m$  (where  $m$  is the number of comparisons to be made) to account for increases in the Type I error from multiple hypothesis testing. The overall alpha was set at 0.05, and most individual comparisons were conducted at  $\alpha'=0.009$ .

#### Comparisons of Intake Facility Collections and Net Collections

The null hypothesis of no difference in density between samples collected in the canal with bongo nets and samples collected through screens on the intake facility was tested using paired t-tests. The hypothesis was tested separately for each screen condition (1-mm, 2-mm, and 3-mm screens). Comparisons were made using data from both years.

#### Comparison of Entrainment Rates Through Screens of Different Diameter/Through-Slot Velocity

The hypothesis of no difference in the densities of each size class when using screens of different diameter and through-slot velocities (small diameter 2-mm screen at high and low pump speeds, large diameter 2-mm screen at high and low pump speeds) was tested using a blocked one way analysis of covariance. Port-day combinations were treated as a blocking factor and canal density as the covariate. The model used in the analysis was identical to the one used to test for the effect of different slot widths, except that screen diameter/through-slot velocity was substituted for screen slot size.

As with the earlier analysis, when interaction terms were insignificant, they were excluded from the model, and a new fit was made which did not include the insignificant terms. When a significant screen condition effect was found, pairwise comparisons of the adjusted treatment means under varying test conditions were made.

When the covariate was found to be insignificant, or the covariate by screen condition interactions was found to be significant (indicating unequal slopes across treatment groups),

the ANCOVA model was replaced by a blocked one-way ANOVA. Significant differences found using the ANOVA model were tested using Duncan's new multiple range test.

When low numbers resulted in unequal variances across treatment groups that could not be corrected for by transformation, Friedman's rank sum statistic, described earlier, was used. In this case, date-port was used as the blocking factor and screen diameter/through-slot velocity condition was the main effect. When treatment differences were significant, pairwise comparisons of the treatment mean ranks were made (Conover, 1971). The critical values for each pairwise comparison were determined using a Type I error of  $\alpha/2m$  with  $\alpha$  set at 0.05.

### III. RESULTS

The mean values for salinity, dissolved oxygen, and temperature during the 1982 and 1983 study periods are presented in Table III-1. In 1982, salinity ranged from 7.3 - 11.3 ppt with a mean value of 9.0 ppt. Lower salinities were recorded in 1983 ( $\bar{X}$  = 7.2 ppt). Mean water temperature was higher in 1983 than in 1982 (29.1 vs 27.8°C). Dissolved oxygen concentrations were close to saturation in both years.

The species of organisms captured by the model intake facility and by nets towed in the discharge canal were similar in both 1982 and 1983. Naked goby (Gobiosoma bosci) and bay anchovy (Anchoa mitchilli) were the most abundant larval and juvenile fish during the study, with hogchoker (Trinectes maculatus) and silverside (Menidia menidia) larvae captured occasionally. Grass shrimp (Palaemonetes spp.), mysid shrimp (Neomysis americana), and an unidentified isopod of the family Cymothoidae dominated the macroplankton. Amphipods (mostly Leptocheirus) and crab zoea were collected occasionally.

#### A. COMPARISON OF ENTRAINMENT RATES THROUGH SCREENS OF DIFFERENT SLOT WIDTH AND AN OPEN PORT

Screens had the effect of lowering entrainment rate, relative to an open port, for all but the smallest size category of both species and their eggs. The degree of entrainment reduction was dependent on fish size, with larger ichthyoplankton more successfully excluded. Screen slot size had some effect on entrainment rates, but the effect was not large.

#### Anchovies

Tables III-2 and III-3 show the mean density of anchovies, captured by size class under each screen condition in 1982 and 1983, respectively. The size distribution of anchovies present in the ambient waters (as measured by the bongo net collections and the open port) varied between years. Eggs and smaller larvae were prevalent in July 1983, whereas in August 1982 no eggs were found and the larger size classes predominated.

The data for bay anchovy met the assumptions of parametric statistics for most size classes. However, it was necessary to use nonparametric methods for size class 2 (5-7 mm) in 1982,

Table III-1. Salinity, dissolved oxygen concentration, and surface water temperature during the studies in 1982 and 1983.

		Salinity (ppt)	Dissolved Oxygen (ppm)	Temperature (°C)
1982	Mean	9.0	7.6	27.8
	Range	7.3-11.3	4.3-10.5	25.9-28.9
1983	Mean	7.2	6.9	29.1
	Range	4.6-9.9	5.5-9.6	27.1-31.5

Table III-2. Mean density (per 1000 m<sup>3</sup>) of bay anchovy collected with each device by size class in 1982.

Size Class	Bongo Net	Open Port	2-mm Screen	1-mm Screen
Eggs	0.0	0.0	0.0	0.0
$\leq 4$ mm	2.0	0.0	0.0	0.0
5-7 mm	4.5	4.1	0.0	0.0
8-10 mm	6.2	1.6	1.5	0.0
11-14 mm	152.9	31.1	10.5	0.0
$\geq 15$ mm	2,469.4	57.3	15.0	1.5

Table III-3. Mean density (per 1000 m<sup>3</sup>) of bay anchovy collected with each device by size class in 1983.

Size Class	Bongo Net	Open Port	3-mm Screen	2-mm Screen	1-mm Screen
Eggs	19610	2341	1707	18435	10966
$\leq 4$ mm	6.0	9.6	13.6	21.0	9.2
5-7 mm	37.6	20.1	11.3	9.2	10.8
8-10 mm	11.2	7.7	2.6	1.6	1.0
11-14 mm	3.5	1.3	0.3	0.0	0.0
$\geq 15$ mm	9.3	3.3	0.5	0.4	0.0

for size class 4 (11-14 mm) in both years, and for size class 5 ( $> 15$  mm) in 1983. Except for class 3 (8-10 mm) in 1983, use of canal density as a covariate was ineffective for bay anchovies.

Table B-1 presents the results of ANOVA for anchovy eggs. No significant screen effect was found. Although there was a large difference in the mean number of eggs entrained through the open port and the 1 and 2-mm screens, however this difference was small relative to the large variability associated with capture of eggs.

There was no observed effect of screen size on entrainment of anchovies in size class 1 ( $\leq 4$  mm). ANOVA performed on 1983 data showed screen effect to be insignificant for this size class (Table B-2). In 1982, no anchovies of this size class were captured through the intake facility (Table III-2).

There was a statistically significant effect of screen size on entrainment of size class 2 (5-7 mm) bay anchovies in 1983, but not in 1982. In 1983 the open port collected approximately twice as many organisms as any of the screens (Table III-2). Entrainment through the open port was significantly different from entrainment through all screens (Table B-3), but no difference could be detected among the different screens. In 1982, no size class 2 (5-7 mm) anchovies were captured through either the 1 or 2-mm screens (Table III-2). However Friedman's Test did not show these screens to reduce entrainment significantly ( $\chi^2 = 3.6$ ,  $p = .17$ ), as only 5 individuals of this size class were collected through the open port in 1982.

The effect of screen size on size class 3 (8-10 mm) bay anchovies was significant in 1983, but not in 1982. In 1982, no size class 3 anchovies were captured through the 1 mm screen, and the few captured through the open port and 2 mm screen were insufficient to allow detection of a screen effect (Table B-4). In 1983, significantly more anchovies of this size class were collected through the open port than through any of the screens (Table B-5). There were no significant differences in entrainment for the different screen sizes (Table B-5).

In both years of the study, there was a significant screen effect for the 11-14 mm size class of anchovies. Friedman's test conducted with 1982 data showed that the number of anchovies collected through the open port was significantly greater than that through the 1-mm screen ( $\chi^2 = 12.2$ ,  $p < .01$ ). However, entrainment through the open port was not significantly different from entrainment through the 2-mm screen, nor was the 1-mm screen different from the 2-mm screen. Friedman's test on 1983 data showed significant differences between the open port and all screen sizes ( $\chi^2 = 22.4$ ,  $p < .01$ ), but no differences among screens (Table B-6). Anchovies of this size class were

not captured through a 1-mm screen in either year, and in 1983 none were captured through the 2-mm screen.

The open port captured many times more size class 5 (> 15mm) bay anchovies in 1982 than the 1 or 2-mm screens (Table III-2). Differences in numbers collected under the different test conditions were significant (Table B-7). In 1983, no anchovies of this size class were collected through the 1-mm screen (Table III-3). Friedman's test showed a significant screen effect ( $\chi^2 = 29.97$ ,  $p < .01$ ). The open port collected a significantly greater number of anchovies than were entrained through any screen, but no significant difference in entrainment among screens of different sizes was found.

### Naked Gobies

Tables III-4 and III-5 present the mean number collected through screens of each size for the four naked goby size classes in 1982 and 1983, respectively. As with bay anchovies, more individuals of small size were present in ambient waters in July 1983 than in August 1982. More individuals of large size were present in the 1982 study (as measured by bongo net and open port collections) than in 1983.

Parametric methods were found to be appropriate for all naked goby analyses except that for the 1983 size class 4 (> 9 mm) data. Canal density as a covariate was found to be appropriate for size classes 1 (<4 mm) and 2 (5-6 mm) in both years, but not for size classes 3 (7-8 mm) and 4 (> 9 mm) in either year.

No significant screen effect was found for size class 1 (< 4 mm) in either 1982 (Table C-1) or 1983 (Table C-2). In 1982, the mean number of individuals captured through the 1-mm screen was less than 10% of that collected through the open port (Table III-4); however, this was found to be statistically insignificant using ANOVA ( $p = .63$ , Table C-1). In 1983, the mean number of individuals captured through the open port varied by less than 5% from the mean value of fish captured through any of the screens (Table III-5); these differences were also statistically insignificant (Table C-2).

The effect of screen slot size was found to be significant for 5-6 mm naked gobies in 1983 (Table C-3), but not in 1982. In 1983, the 1-mm screen captured significantly fewer individuals of this size class (250%) than the open port (Table C-3). The 1-mm screen collected significantly fewer individuals than the 2-mm or 3-mm screens. The numbers collected through the larger mesh screens did not differ significantly from those collected through the open port (Table C-3). In 1982, the 1-mm screen

Table III-4. Mean density (per 1000 m<sup>3</sup>) of naked goby collected with each device by size class in 1982.

Size Class (mm)	Bongo Net	Open Port	2-mm Screen	1-mm Screen
$\leq 4$	95.3	17.2	13.5	1.5
5-6	117.6	22.9	19.5	6.0
7-8	95.5	38.5	16.5	5.8
$\geq 9$	342.3	201.5	64.6	35.8

Table III-5. Mean density (per 1000 m<sup>3</sup>) of naked goby collected with each device by size class in 1983.

Size Class (mm)	Bongo Net	Open Port	3-mm Screen	2-mm Screen	1-mm Screen
≤ 4	223.5	535.7	557.1	513.4	562.5
5-6	514.8	148.7	87.6	81.6	66.5
7-8	370.5	49.7	11.2	9.6	3.9
≥ 9	243.7	49.1	7.8	4.4	1.9

also collected less than half the number of 5-6 mm individuals collected through the open port (Table III-4), but the screen effect was not found to be significant (Table C-4).

Tables C-5 and C-6 show results of ANOVA for the 7-8 mm size class in 1982 and 1983, respectively. The screen effect was significant, and the open port collected a significantly greater number of individuals than all screens in both years. The 1-mm screen collected significantly fewer individuals than the 2-mm screen in 1982 (Tables III-4 and C-5), and significantly fewer than the 2 or 3-mm screen in 1983 (Tables III-5 and C-6).

The screen effect was found to be significant for the > 9 mm size class in both years of the study. In 1982, both the 1 and 2-mm screened samples contained significantly fewer gobies than the open port, but no difference between the screened samples was found (Table C-7). In 1983, the open port also collected significantly more gobies of this size than each of the screens according to results of the Friedman's test ( $\chi^2 = 39.50$ ,  $p < .01$ ). As in 1982, the effect of the 1-mm screen did not differ significantly from the effect of the 2-mm screen in 1983 tests; however, significantly fewer gobies were entrained through the 3-mm screen.

#### B. COMPARISON OF ENTRAINMENT RATES THROUGH SCREENS OF DIFFERENT SLOT WIDTH AND A BONGO NET

The pattern of exclusion by screens was very similar when compared to bongo nets or when compared with open ports. Screens had the effect of reducing entrainment, relative to density measured with a bongo net, for all but the smallest size category of each species and for eggs. The degree of entrainment reduction increased with fish size, and was affected only to a minor degree by screen slot size.

#### Bay Anchovies

Canal density and densities of concurrent screened samples of each bay anchovy size class are presented in Table III-6. There was no significant difference in density of eggs for screens of any slot size relative to canal density. For the 1-mm and 2-mm screens, mean density in the canal exceeded the screened density three to four fold, but these differences were insignificant due to the high variability associated with ambient egg density.

Table III-6. Mean density (per 1000 m<sup>3</sup>) of bay anchovies collected in bongo nets and screened samples.

Size Class	Canal Density	1-mm Screen	Canal Density	2-mm Screen	Canal Density	3-mm Screen
Eggs	40624	10966 <sup>ns</sup>	54501	18435 <sup>ns</sup>	1546	1707 <sup>ns</sup>
≤ 4 mm	3.6	7.2 <sup>ns</sup>	5.8	16.5 <sup>ns</sup>	7.6	13.6 <sup>ns</sup>
5-7 mm	33.0	8.5*	31.2	7.2*	29.9	11.3*
8-10 mm	7.7	0.8*	10.7	2.4*	10.2	2.6*
11-14 mm	22.1	0.0*	46.9	2.3*	2.6	0.3 <sup>ns</sup>
≤ 15 mm	516.0	0.3*	677.9	3.5*	77.3	0.5*

\*Significantly different from the canal density at  $\alpha = 0.05$

Although the density of bay anchovy size class 1 ( $\leq 4$  mm) in screened samples always exceeded canal density, none of the differences were statistically significant. For all other size classes, the density in the canal was always higher than that of screened samples. All the comparisons were statistically significant, except for that between 3-mm screen density and canal density for size class 4 (11-14 mm) anchovies. In this comparison, the density through the screen was only about 10% of the density estimated from the bongo net collections, but low numbers of fish were taken with both devices, which probably accounts for the lack of significance.

### Naked Gobies

Table III-7 shows the mean density of naked gobies for each size class collected in screened samples compared with canal densities. All comparisons of bongo net samples and screened samples for naked gobies were statistically significant, but the direction of the difference was dependent on fish size. The density of gobies in size class 1 ( $\leq 4$  mm) was always greater in screened samples than in the canal samples. However, for all other size categories, the canal samples had a considerably higher mean density than screened samples.

### C. COMPARISON OF ENTRAINMENT RATES THROUGH 2-MM SCREENS OF DIFFERENT DIAMETER AND THROUGH-SLOT VELOCITY

The four combinations of screen diameter and through-slot velocity were not found to affect entrainment of bay anchovies, but did affect that of naked gobies. Density of naked goby in our samples generally increased with higher through-slot velocity, but was dependent on fish size.

### Bay Anchovies

Table III-8 shows the mean density for each bay anchovy size category collected through 2-mm screens of different diameter and through-slot velocity. The assumptions of parametric statistics were met for all size classes except size class 5 ( $> 15$  mm). The canal density was a significant covariate with homogeneous slope only for size class 3 (8-10mm).

Tables D-1 through D-5 show ANOVAS for eggs and fish of size classes 1-4. In none of these cases was the effect of through-slot velocity or screen diameter significant. For size class 5 ( $> 15$  mm), Friedman's test showed that effects of through-slot

Table III-7. Mean density (per 1000 m<sup>3</sup>) of naked gobies collected in paired sets of bongo nets and screened samples.

Size Class	Canal Density	1-mm Screen	Canal Density	2-mm Screen	Canal Density	3-mm Screen
$\leq 4$ mm	174.8	442.3*	198.3	406.3*	202.9	557.1*
5-6 mm	457.7	53.5*	405.2	68.3*	458.9	87.6*
7-8 mm	353.2	4.3*	276.0	11.1*	325.3	11.2*
$\leq 9$ mm	295.2	9.2*	257.0	17.3*	211.0	7.8*

\*Significantly different from the canal density at  $\alpha = 0.05$

Table III-8. Mean density (per 1000 m<sup>3</sup>) of each bay anchovy size class collected through screens with different through-slot velocity and screen diameter.

Screen Diameter		Large	Large	Small	Small
Pump Speed		Low	High	Low	High
Through Slot Velocity (cm/sec)		9.5	20	19	40
Fish Size (mm)	Eggs	22229	18435	24752	3358
	2-4	23.7	21.0	32.3	8.8
	5-7	15.7	9.2	16.3	13.0
	8-10	1.9	1.6	3.3	3.3
	11-14	0.0	0.0	0.3	0.5
	15-19	0.3	0.4	0.8	0.8
	>19	0.3	0.4	0.8	0.8

velocity and screen diameter were insignificant ( $\chi^2 = 3.0$ ,  $p = .39$ ). These findings are supported by the data in Table III-8, which show no consistent pattern of large differences in entrainment rates for different test conditions. It appears that for bay anchovies, neither screen diameter nor through-slot velocity, within the range tested, affected entrainment through the screens.

#### Naked Gobies

Table III-9 shows the mean density for each naked goby size class collected through 2-mm screens of different diameter and through-slot velocity. For all size categories, the assumptions necessary for use of parametric statistics were met. The covariate was found to be significant only for size classes 1 ( $\leq 4$  mm) and 2 (5-6 mm).

Unlike results obtained for bay anchovies, the through-slot velocity and screen diameter effect was significant for every naked goby size class (Tables E-1 to E-4). There were some minor differences in rank order for different test conditions, but the small screen at high pump speed always captured the greatest density of gobies. For size categories 1 ( $\leq 4$ -mm) and 2 ( $\leq 5$ -6-mm) gobies, the magnitude of difference between this and other screen conditions was relatively small ( $\leq 50\%$ ). For goby size categories 3 ( $> 7$ -8-mm) and 4 ( $> 9$ -mm), the difference increased to more than 100% (Table III-9).

ANOVA done on size category 1 ( $\leq 4$  mm) showed that screens of both large and small diameter collected significantly more individuals per volume filtered when operated at high pump speed than at low pump speed (Table E-1), while collections from screens of different sizes, used with the same pump speed, did not differ. For size class 2 (5-6 mm), both high pump speed conditions entrained a greater density of gobies than the large screen at low pump speed (Table E-2 and Table III-9). No other significant differences were found within this size group. For size classes 3 (7-8 mm) and 4 ( $\geq 9$  mm), the density of fish collected through the small screen operated at high speed was significantly greater than the density under all other conditions, and no other significant differences were found (Tables E-3 and E-4).

Table III-9. Mean density (per 1000 m<sup>3</sup>) of each naked goby size class collected through screens with different through-slot velocity and screen diameter.

Screen Diameter		Large	Large	Small	Small
Pump Speed		Low	High	Low	High
Through-Slot Velocity (cm/sec)		9.5	20	19	40
Fish Size (mm)	≤ 4	400.5	513.4	424.8	598.6
	5-6	58.4	81.6	109.4	119.2
	7-8	6.6	9.6	7.7	27.1
	≥ 9	4.7	4.4	3.6	11.4

#### IV. DISCUSSION

##### Do Screens Reduce Entrainment Relative to an Open Port?

Entrainment rates of bay anchovy eggs and of larvae 4 mm in length or less, were not significantly affected by screens. However, approximately 50% of the 5 to 7 mm bay anchovies were excluded in comparison with an open port. Individuals greater than 7 mm long were increasingly excluded with size. For anchovies greater than 10 mm in length, almost 100% exclusion by a 1-mm screen was noted. In the case of naked gobies, fish 4 mm in length or less were not excluded by screens when entrainment rates were compared to those for an open port. Exclusion began to occur for fish of 5 to 6 mm, and exceeded 90% for gobies 7 mm or longer when using a 1-mm screen. Tables IV-1 and IV-2 show screening efficiency for each size class of bay anchovy and naked goby, respectively.

The degree of physical exclusion should be expected to increase as fish grow larger. Figures IV-1 and IV-2 show the relationship between body length and head width for bay anchovies and naked gobies, respectively. Physical exclusion by screens might not be expected for fish of both species 4 mm in length or less, since their average head width is less than 0.5 mm. On the other hand, fish greater than 8 mm long are close to, or exceed, 1 mm in width and should not be entrained through 1 mm slot width screens. Data from the study support this. For bay anchovies, only a single individual above 8 mm in length was ever caught through a 1-mm screen, and the exclusion efficiency of a 1-mm screen was 95% for naked gobies larger than 7 mm.

Swimming performance and ability to avoid flow fields also increase with fish size, and probably contributed to exclusion of larger fish. Hanson (1981) observed that striped bass under 7 mm in total length (TL) do not possess sufficient swimming ability to avoid screens under laboratory conditions, whereas larger fish do. In our study, individuals of either species 4 mm (SL) in length or less were not excluded by screens. Bay anchovy eggs possess no swimming ability and were not excluded by 1-mm screens according to both this study and the study of Browne et al, (1981), even though the eggs exceed 1 mm in diameter. In contrast, individuals larger than 4 mm were excluded by all screens in our study, even though they could easily pass through screens with 2 and 3-mm slot width.

Table IV-1. Exclusion efficiencies of bay anchovies for three screen sizes, compared to an open port and to canal density.

	Efficiency Compared to an Open Port (a)			Efficiency Compared to Canal Density (b)		
	1-mm Screen	2-mm Screen	3-mm Screen	1-mm Screen	2-mm Screen	3-mm Screen
Eggs	-368.4ns	-687.5ns	27.1ns	73.0ns	66.2ns	-10.4ns
< 4	4.5ns	-118ns	-41.7ns	-100.0ns	-184.5ns	-78.9ns
5-7	47.1*	55.5*	45.3*	74.2*	76.9*	62.2*
8-10	87.2*	77.8*	66.2*	89.6*	77.6*	74.5*
11-14	100*	77.8*	76.9*	100.0*	95.1*	88.5ns
> 15	98.7*	80.0*	84.8*	99.9*	99.5*	99.4*

(a) Exclusion efficiency =  $\frac{\text{Open port density} - \text{Screen density}}{\text{Open port density}}$

(b) Exclusion efficiency =  $\frac{\text{Canal density} - \text{Screen density}}{\text{Canal density}}$

\* Significant at  $\alpha = .05$

Table IV-2. Exclusion efficiencies of naked gobies for three screen sizes, compared to an open port and compared to canal density.

Size Class (mm)	Efficiency Compared to an Open Port (a)			Efficiency Compared to Canal Density (b)		
	1-mm Screen	2-mm Screen	3-mm Screen	1-mm Screen	2-mm Screen	3-mm Screen
< 4	-4.7ns	4.2ns	-4.0ns	-153.0*	-104.9*	-174.6*
5-6	55.5*	44.7ns	41.1ns	88.3*	83.1*	80.9*
7-8	97.3*	79.3*	77.5*	98.8*	96.0*	96.6*
> 9	92.6*	85.1*	84.1*	96.9*	93.3*	96.3*

(a) Exclusion efficiency =  $\frac{\text{Open-port density} - \text{Screen density}}{\text{Open-port density}}$

(b) Exclusion efficiency =  $\frac{\text{Canal density} - \text{Screen density}}{\text{Canal density}}$

\* Significant at  $\alpha = .05$

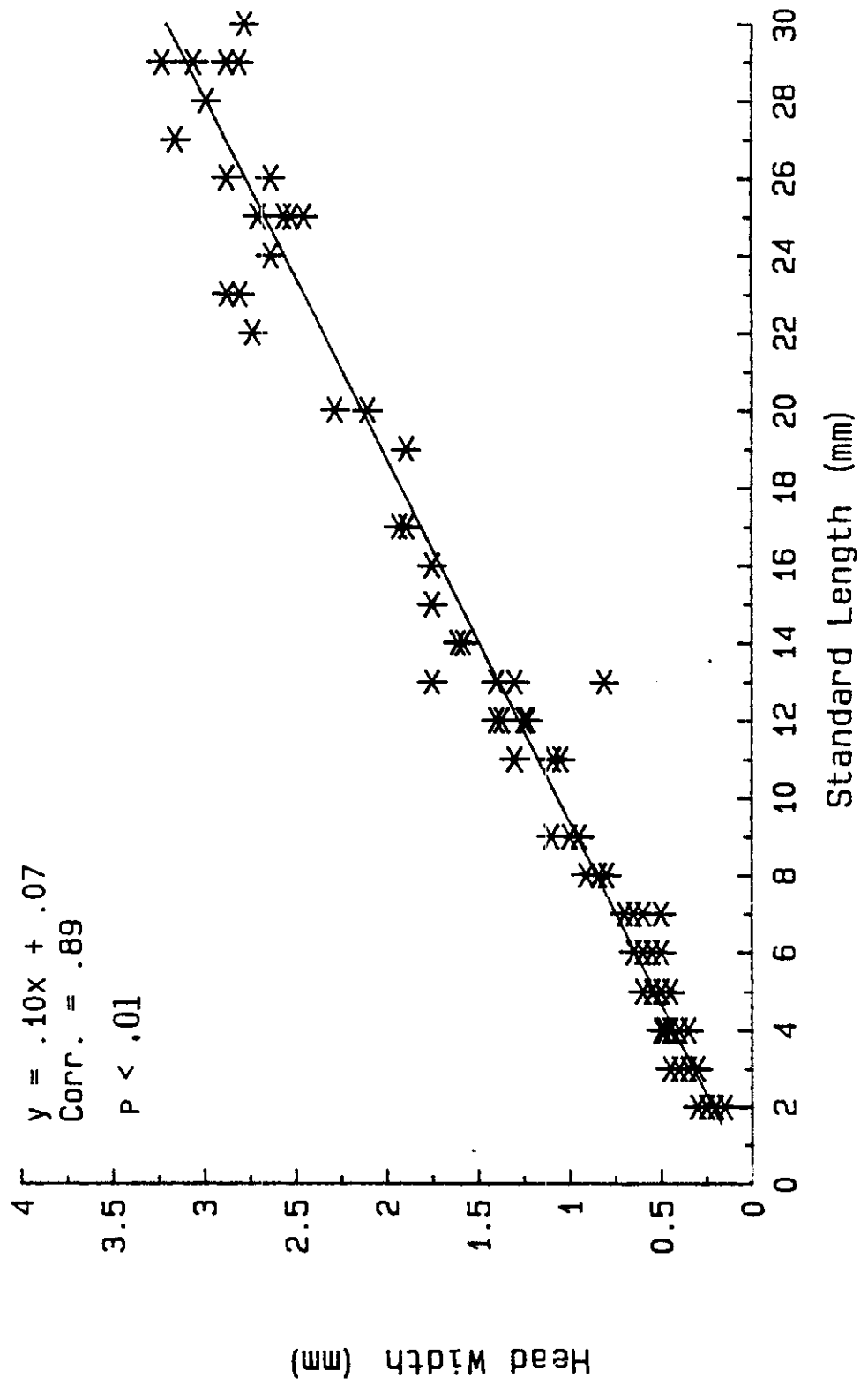


Figure IV-1. Relationship of standard length to head width for bay anchovy

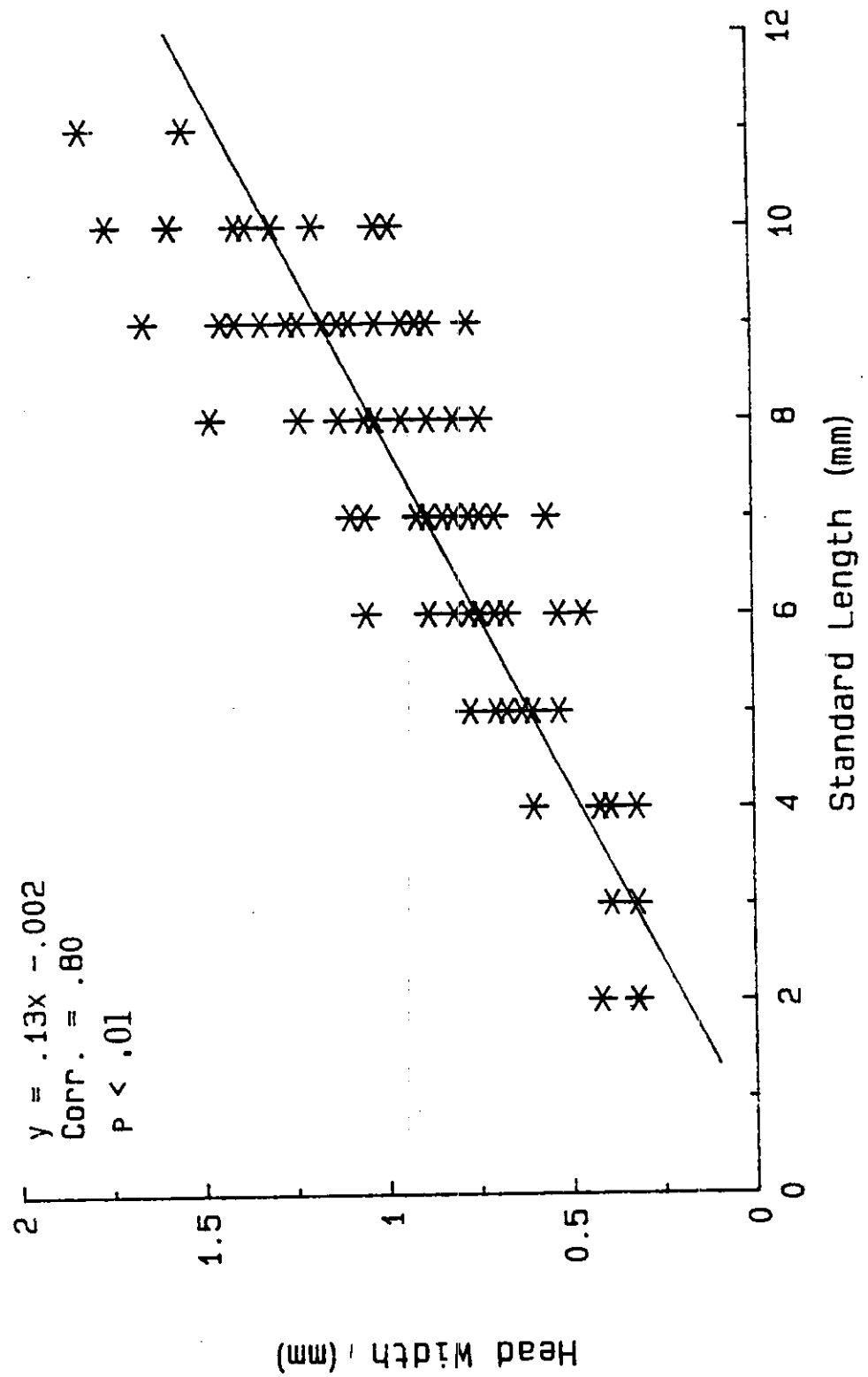


Figure IV-2. Relationship of standard length to head width for naked goby

Other studies have also shown that fish size is an important determinant of screening efficiency. In flume studies conducted by Hanson (1981), yellow perch of less than 8 mm (TL) were not excluded by a 1-mm screen. Exclusion efficiency increased with increasing fish size and became 100% when yellow perch reached 13 mm (TL). A similar pattern, with total exclusion at 11 mm (TL), occurred for striped bass. In field studies with a 1-mm screen, exclusion of striped bass was insignificant for individuals less than 10 mm (TL), but was greater than 90% for individuals larger than 11 mm, Delmarva Ecological laboratory (1980). They also found similar size related patterns for other fish species. This was the only other study in which the effect of fish size on screening efficiency in the field has been examined. However, in several field studies it has been noted that the maximum size of fish entrained through 1-mm screens is less than that collected through open ports or towed nets (Dames and Moore, 1979; Otto et al., 1981; Zeitoun et al., 1981).

In the present study, fish size was found to be important in determining the effectiveness of wedge-wire screens. In many other studies of reduction in entrainment through wedge-wire screens, the effect of fish size has not been examined, which may help to explain why apparent inconsistencies in conclusions were reached by previous researchers. Dames and Moore (1979) and Delmarva Power and Light (1982) both found close to 100% exclusion of bay anchovies in comparison to Browne et al., (1981) who found only 61% exclusion. The mean size of anchovies was not given in the first two studies, and may have been large. In contrast, the mean size of anchovies collected through the open port in the study of Browne et al., was only 4.2 mm (TL). In the case of naked gobies, Dames and Moore (1979) found 56% exclusion efficiency through a 1-mm screen, while Browne et al., (1981) found no significant difference between collection through a 1-mm screen and through an open port. Again the small mean size of gobies entrained through the open port in the later study (4.8 mm) may have led to their lesser estimate of exclusion.

#### Do Screens Reduce Entrainment Relative to Canal Density?

Tables IV-1 and IV-2 show screening efficiency compared to canal density for 1, 2 and 3-mm screens. The pattern of exclusion is very similar to that observed when screens were compared with an open port, i.e., screens effectively reduced entrainment, though the magnitude was dependent on fish size. For bay anchovies, entrainment of eggs or individuals less than 5 mm in length was not significantly affected by screens. Individuals larger than 5 mm were excluded in comparison to either open port or canal density, though the magnitude of exclusion was greater in relation to canal density. For anchovies

larger than 14 mm, the exclusion efficiency of all screen sizes tested exceeded 99% in relation to canal density.

Naked gobies of 4 mm in length or less were captured in significantly greater numbers in screened samples than in bongo net samples. The attraction through the screens indicated by these data could be due to this species' habitat preference for structures. Naked gobies were often observed during the study swimming in or near the biofouling community that developed on the barge. This behavior would tend to cause underestimates of ambient density when measured by the bongo net, which was towed upstream of the barge. For gobies greater than 4 mm in length, screens significantly reduced entrainment in relation to canal density. For gobies larger than 6 mm, exclusion was always greater than 90%.

In our study, as well as in others, towed net samples have almost always been shown to contain more ichthyoplankton than unscreened port samples. This is not surprising, since an unscreened port creates a flow field which ichthyoplankton can detect and avoid (Hocutt and Edinger, 1980). Bongo nets, on the other hand, are an active collection method and are generally towed at speeds which make avoidance by smaller ichthyoplankton unlikely. When calculating screening efficiency, the use of towed net samples as a control will therefore result in exclusion efficiencies higher than those found when using unscreened ports.

We have presented exclusion efficiency using both methods as reference points. For most fish size classes, the conclusion reached in our study would be the same using either method, though the magnitude of exclusion would vary. The open port method is the more conservative approach and is our recommended method for estimating entrainment reduction. However, the towed net method should not be discounted. Several authors have shown that ichthyoplankton estimates increase with increasing boat speed up to about 8 m/sec (Thayer et al. 1983; Colton et al. 1980; Clutter and Anraku, 1968). Since our tows were conducted at a boat speed of approximately 0.5 m/sec., they may still produce underestimates of actual numbers present in the ambient waters.

#### Did Screen Slot Size Affect the Numbers Collected?

In this study, fewer individuals of both species were entrained through the 1-mm screen than through the 2 or 3-mm screens. For most size classes of naked gobies these differences were significant. However, for several size classes of bay anchovies, the difference in entrainment rates among different screens was not significant. Examination of the data indicates that the lack of statistical significance may be an artifact of low numbers. For example, not a single anchovy in the 11 to 14 mm size class was entrained through a 1-mm screen in our

tests. Total exclusion by 2 or 3-mm screens was not observed. However, because of low ambient anchovy abundance, and the 70-80% exclusion offered by 2 and 3-mm screens, sufficient samples containing no anchovies were collected through the larger screens so that these results could not be statistically distinguished from those for the 1-mm screen.

In other studies that have compared entrainment through screens of different slot size, the mean number of individuals collected through the larger screen has always been greater. In the study by Dames and Moore (1979), the difference in fish collected when using a 1 and 2-mm screen was only 8%. However, Browne et al. (1981) found, on the average, 80% greater entrainment of naked gobies and bay anchovies through a 2-mm screen than through a 1-mm screen. Zeitoun et al. (1981) found, on the average, that 40% more individuals were entrained through a 2-mm screen than through a 9.5-mm screen.

Thus, a consistent trend has been found in all studies; larger mesh screens entrain more organisms but the differences are not statistically significant. There are two possible explanations for the lack of statistical significance. First, this may be due to low numbers captured, as was the case with bay anchovies in our study. With low numbers variance tends to increase and small differences become difficult to detect. Secondly, in all of the studies mentioned above, fish of different size classes were grouped together for analysis. However, different size groups behave differently with respect to screen size. Small individuals may not be affected by changes in slot size if they can pass through the smallest slot sizes (e.g., the fish  $< 4$  mm size in our study). Similarly, large individuals will not be affected by changes in screen slot size if they are so large as to be physically excluded by all screens or possess sufficient swimming ability to avoid entrainment through screens of all sizes. When analysis is conducted on data that is pooled over several size groups, the increased variance may obscure significant patterns that occur only within a limited size range.

#### Did Screen Diameter Affect the Numbers Captured?

Screen diameter appeared to have little effect on the number of ichthyoplankton entrained. The effect of screen diameter on the number of individuals captured was determined by comparing the large diameter 2-mm screen at high pump speed with results for the small diameter 2-mm screen at low pump speed. Both screens had the same through-slot velocity. For bay anchovies there was no statistical difference. For naked gobies, only for the smallest category was there a significant difference. In the latter case, the large screen at high pump speed collected approximately 20% more fish.

### Did Through-Slot Velocity Affect the Numbers Captured?

The effect of through-slot velocity on the density of individuals collected can be discerned by comparing effects of screens of identical diameter and slot width size, but of different withdrawal rates. In our study, such a comparison was made twice: between the effects of high and low pumping rate when the large diameter 2-mm screen was used (20 cm/sec and 9.5 cm/sec through-slot velocity, respectively), and the effects of high and low pumping rate when the small diameter 2-mm screen rate was used (40 cm/sec and 19 cm/sec, respectively).

The density of bay anchovies did not differ when collected through screens with different through-slot velocity. The number of bay anchovies collected through 2-mm screens, particularly for the larger size classes, was low. No consistent differences in the mean density of individuals collected under different conditions were apparent (Table III-8), though the low numbers may have hampered our ability to detect significant differences.

For every naked goby size class, the greatest density was found in samples taken at the highest through-slot velocity (Table III-9). Significant differences were observed for the smallest size class of gobies between 9.5 cm/sec and 20 cm/sec., as well as between 19 cm/sec and 40 cm/sec. For the two largest goby size classes, significant differences were found only between 19 cm/sec and 40 cm/sec. This pattern suggests that the swimming ability of smaller gobies is sufficient to overcome through-slot velocities of 9.5 cm/sec, but not of greater withdrawal rates, and that larger gobies can overcome velocities as great as 20 cm/sec but not as great as 40 cm/sec.

In tests of screen slot size, swimming ability was undoubtedly important in reducing entrainment of both species through screens with slots too large to exclude them physically (i.e., 2, and 3-mm screens). Therefore, it is surprising that entrainment of bay anchovies was not affected by changes in the flow field. The through-slot velocities we chose to test may have been too low to affect anchovies, but high enough to affect naked gobies. Hanson et al. (1978) used anchovies in tests with through-slot velocities that were higher than those we used, and found little effect on the fish. However, anchovies used in tests by Hanson et al. were larger than those in our studies and it is unlikely that the anchovies in our study could escape currents of 40 cm/sec. Further, maximum swimming speed of most larval fish, including anchovy (Webb and Corolla, 1981) and goby (Logachev and Mordvinov, 1979) species, is generally less than 10 cm/sec (e.g., Blaxter, 1969; Hettler, 1978; Hartwell and Otto, 1978; Turnpenny and Bamber, 1983). Even 15 mm anchovies would not possess enough swimming ability to escape the 40 cm/sec through-slot velocity used in our tests.

A better explanation for differences in response to through-slot velocity may include differences in behavior of the two species, along with the differences in swimming ability. Naked gobies tend to prefer structures and were observed swimming very close to the screen, as if feeding on detritus drawn toward it. Anchovies were not observed to move as close to the screen on a regular basis. The through-slot velocities used in this test were quickly dissipated by the screen's circular configuration. In our attempts at measuring flow, water withdrawal was indistinguishable from ambient flow at a distance of less than 10 cm from the screen surface. Gobies, because they swim close to the screen, should be more affected by this change in their local environment than anchovies, which generally remain outside this flow field.

## V. CONCLUSIONS

In this study we have shown that the effectiveness of wedge-wire screens in reducing entrainment is dependent on fish size. Evidence for exclusion by maintenance of low through-slot velocities as well as by physical exclusion, were apparent. A 1-mm screen reduced entrainment of both species when they reached 5 mm in length. Below that size, no exclusion by screens was apparent. Above 10 mm in length, virtually total exclusion by 1-mm screens occurred for both species.

Screen slot size had an effect on the number of fish entrained, but the effect was not large. A 1-mm screen was found to represent a barrier for 100% of the larger fish, while screens with larger slots excluded ~ 80% of the ichthyoplankton relative to an open port.

Altering through-slot velocity over a four-fold range affected entrainment of naked gobies but not of bay anchovies. Due to the circular configuration of the screens, inward flow vectors quickly dissipate. We suggest that species such as naked gobies, which inhabit areas near the screen, will be affected more by these changes in flow than will open water species such as anchovies, which typically remain outside the influence of the withdrawal field.

The effect of screen diameter was found to be rather unimportant, particularly for larger fish. For small individuals there was a slight reduction in entrainment with a lower withdrawal rate.

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APPENDIX A

TEST CONDITIONS, SURFACE SALINITY, TEMPERATURE, AND  
DISSOLVED OXYGEN FOR EACH NIGHT DURING  
THE 1983 ENTRAINMENT STUDY

Table A-1. Test conditions for 1983 entrainment study  
Date: 12 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2121	6.0	28.2	9.08	2L	H	2S	H
2	2224	6.1	28.4	8.77	0	H	3	H
3	2312	6.0	27.9	9.2	2L	H	3	H
4	2400	6.0	28.3	9.7	2L	L	2S	L
5	2456	6.3	28.3	9.14	1	H	2L	L
6	0150	5.7	28.0	9.16	2S	H	1	H
7	0232	5.4	27.7	7.74	2S	L	0	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-2. Test conditions for 1983 entrainment study Date: 13 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2115	5.8	27.3	7.94	3	H	2S	H
2	2156	6.1	28.2	7.74	1	H	2S	L
3	2246	6.2	27.2	7.82	2L	H	1	H
4	2340	6.0	27.4	7.79	2L	L	3	H
5	2426	5.9	27.9	7.99	0	H	2L	H
6	0110	5.5	28.5	6.61	2S	L	0	H
7	0151	5.5	28.5	6.91	2S	H	2L	L

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-3. Test conditions for 1983 entrainment study Date: 14 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2055	5.4	29.0	9.1	2S	L	2L	L
2	2153	5.8	28.9	8.21	3	H	1	H
3	2255	6.0	29.0	7.91	2S	H	3	H
4	2339	6.0	28.9	7.95	1	H	0	H
5	2426	6.0	28.6	7.8	2L	L	2S	H
6	0115	5.9	28.6	7.68	0	H	2L	H
7	0157	6.0	28.4	7.0	2L	H	2S	L

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-4. Test conditions for 1983 entrainment study Date: 17 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2106	6.0	29.8	6.59	2S	H	0	H
2	2152	6.0	29.8	6.58	2L	H	2S	H
3	2233	6.0	29.5	6.05	3	H	2S	L
4	2320	6.0	29.4	6.04	0	H	1	H
5	2430	6.0	29.4	6.40	2L	L	3	H
6	0114	6.0	29.3	6.42	2S	L	2L	L
7	0157	6.5	29.2	6.40	1	H	2L	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-5. Test conditions for 1983 entrainment study Date: 18 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2158	6.0	30.4	---	1	H	3	H
2	2243	6.0	30.4	---	3	H	2S	H
3	2328	5.0	30.1	---	2S	H	2L	L
4	2414	6.0	30.0	---	0	H	1	H
5	0101	6.0	29.9	---	2L	L	2S	L
6	0144	6.0	29.9	---	2L	H	0	H
7	0233	6.0	29.8	---	2S	L	2L	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-6. Test conditions for 1983 entrainment study Date: 19 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port				Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed	Screen Type	Pump Speed
1	2109	6.5	30.6	8.34	0	H	2L	H	2L	H
2	2149	6.0	30.5	7.4	3	H	2L	H	2L	L
3	2230	6.1	30.2	7.0	2L	H	2S	H	2S	L
4	2311	6.0	30.0	5.6	2S	L	0	L	0	H
5	2353	6.0	30.0	5.5	1	H	2S	H	2S	H
6	2444	6.0	29.8	5.6	2L	L	3	L	3	H
7	0111	6.0	29.7	5.7	2S	H	1	H	1	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-7. Test conditions for 1983 entrainment study Date: 20 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2113	6.9	31.5	9.93	2L	L	2S	H
2	2212	6.9	31.0	7.10	3	H	1	H
3	2301	6.7	30.4	6.3	0	H	2S	L
4	2350	6.4	30.4	6.2	1	H	3	H
5	2438	6.5	30.4	6.1	2L	H	0	H
6	0122	6.5	30.5	6.05	2S	L	2L	H
7	0205	6.5	30.2	5.72	2S	H	2L	L

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-8. Test conditions for 1983 entrainment study Date: 21 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2102	7.7	31.2	8.4	2S	L	2L	L
2	2202	7.7	31.3	9.2	2S	H	2L	H
3	2250	7.7	30.8	5.9	2L	L	2S	H
4	2333	7.2	30.7	5.9	2L	H	1	H
5	2419	6.9	30.3	6.1	3	H	2S	L
6	0103	7.2	30.3	6.0	1	H	0	H
7	0147	7.0	30.1	5.6	0	H	3	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-9. Test conditions for 1983 entrainment study Date 24 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port		Right Port	
					Screen Type	Pump Speed	Screen Type	Pump Speed
1	2116	9.0	28.7	7.35	2L	H	2S	L
2	2204	9.1	28.6	7.2	3	H	1	H
3	2255	8.9	29.0	7.5	2S	H	2L	L
4	2345	8.9	28.8	7.4	1	H	3	H
5	2420	9.1	28.4	6.9	0	H	2L	H
6	0115	9.1	28.8	5.8	2L	L	2S	H
7	0156	8.6	28.9	5.7	2S	L	0	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-10. Test conditions for 1983 entrainment study Date: 25 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port			Right Port		
					Screen Type	Pump Speed	Screen Type	Pump Speed	Screen Type	Pump Speed
1	2111	8.7	28.1	8.70	3	H	0	H	0	H
2	2155	8.8	28.1	8.85	0	H	1	H	1	H
3	2239	8.8	28.1	9.02	2L	L	2S	L	2S	L
4	2324	8.8	27.8	7.88	2S	H	2L	H	2L	H
5	2404	9.0	27.2	7.93	1	H	2L	H	2L	L
6	0101	9.4	27.4	5.06	2S	L	3	L	3	H
7	0140	9.4	27.6	4.58	2L	H	2S	H	2S	H

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

Table A-11. Test conditions for 1983 entrainment study Date: 28 July 83

Replicate	Time	Salinity (ppt)	Temperature (°C)	Dissolved Oxygen (ppm)	Left Port			Right Port		
					Screen Type	Pump Speed	Screen Type	Pump Speed	Screen Type	Pump Speed
1	2101	9.5	28.7	6.8	3	H	2L	L		
2	2141	9.5	28.8	6.83	2S	H	0	H		
3	2219	9.5	28.8	7.21	0	H	2L	H		
4	2304	9.5	27.5	7.37	1	H	3	H		
5	2346	9.6	27.9	7.33	2L	H	2S	H		
6	2424	9.2	27.8	6.97	2L	L	2L	L		
7	0106	9.2	27.9	7.51	2S	L	1	H		

1 = 1-mm screen, 2S = 2-mm small screen, 3 = 3-mm screen, 0 = no screen  
 2L = 2-mm large screen

L = low pump speed, H = high pump speed

APPENDIX B

ANALYSIS OF VARIANCE TABLES  
FOR THE EFFECT OF SCREEN SLOT SIZE ON  
BAY ANCHOVY ENTRAINMENT

Table B-1. Two-way analysis of variance for 1983 data on bay anchovy eggs using date-port as a blocking factor and screen size (open, 1-mm, 2-mm, and 3-mm) as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	209.29	0.99	.49
Screen	3	37.15	1.03	.30
Error	63	636.49		

Table B-2. Two-way analysis of variance for 1983 data on size class 1 (2-4 mm) bay anchovy using date-port as a blocking factor and screen size (open, 1-mm, 2-mm, and 3-mm) as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	42.801	2.99	<.01
Screen	3	2.789	1.37	.26
Error	63	42.89		

Table B-3. Two-way analysis of variance for 1983 data on size class 2 (5-7 mm) bay anchovy using date-port as a blocking factor and screen size (open, 1-mm, 2-mm, and 3-mm) as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	38.432	4.02	<.01
Screen	3	6.308	4.62	.05
Error	63	28.666		

Duncan's New Multiple Range Test For Screen Effect:

<u>open</u>	<u>1-mm</u>	<u>3-mm</u>	<u>2-mm</u>
port	screen	screen	screen

Table B-4. Two-way analysis of variance for 1982 data on size class 3 (8-10 mm) bay anchovy using port (left, right) and screen size (open, 1-mm, and 2-mm) as main effects

Effect	DF	SS	F	P
Port	1	0.00	0.03	.86
Screen	2	0.06	0.38	.69
Error	19	1.50		

Table B-5. Two-way analysis of covariance for 1983 data on size class 3 (8-10 mm) bay anchovy using date-port as a blocking factor, screen size (open port, 1-mm, 2-mm and 3-mm) as a main effect, and canal density as the covariate

Effect	DF	SS	F	P
Port	21	7.152	1.37	.17
Screen	3	9.963	13.32	<.01
Covariate	1	1.040	4.17	.05
Error	62	15.45		

Multiple Comparisons For Screen Effects:

	Open	1-mm	2-mm	3-mm
Open Port	X	<.01	<.01	<.01
1-mm		X	.70	.18
2-mm			X	.33
3-mm				X

Table B-6. Two-way analysis of variance for 1983 bay anchovy data on size class 4 (11-14 mm) using date-port as a blocking factor and screen size (open port, 1-mm, 2-mm and 3-mm) as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	1.28	1.28	.22
		1.43	10.00	<.01
Screen	3			
Error	63	3.00		

Duncan's New Multiple Range Test For Screen Effect:

<u>Open</u> Port	<u>3-mm</u> Screen	<u>2-mm</u> Screen	<u>1-mm</u> Screen
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Table B-7. Two-way analysis of variance for 1982 data on size class 5 ( $\geq 15$  mm) bay anchovy using port (left, right) and screen size (open, 1-mm and 2-mm) as main effects

Effect	DF	SS	F	P
Port	1	1.15	3.07	0.10
Screen —	2	11.32	15.17	<.01
Error	19	7.09		

Duncan's New Multiple Range Test For Screen Effect:

Open	<u>2-mm</u>	<u>1-mm</u>
Port	Screen	Screen

APPENDIX C

ANALYSIS OF VARIANCE TABLES FOR  
THE EFFECT OF SCREEN SLOT SIZE ON  
NAKED GOBY ENTRAINMENT

Table C-1. Two-way analysis of covariance for 1982 data on size class 1 ( $\leq 4$  mm) naked gobies using port (left, right) and screen size (open, 1-mm and 2-mm) as main effects and canal density as the covariate

Effect	DF	SS	F	P
Port	1	2.09	9.79	.01
Screen	2	0.20	0.48	.63
Covariate	1	2.98	14.01	<.01
Error	18	3.83		

Table C-2. Two-way analysis of covariance for 1983 data on size class 1 ( $< 4$  mm) naked goby using date-port as a blocking factor, screen size (open port, 1-mm, 2-mm and 3-mm) as the main effect, and canal density as the covariate

Effect	DF	SS	F	P
Blocking Factor	21	34.082	4.59	$<.01$
Screen	3	1.095	1.03	.38
Covariate	1	2.771	7.83	$<.01$
Error	62	21.935		

Table C-3. Two-way analysis of covariance for 1983 data on size class 2 (5-6 mm) naked goby using date-port as a blocking factor, screen size (open port, 1-mm, 2-mm and 3-mm) as the main effect and canal density as the covariate

Effect	DF	SS	F	P
Blocking Factor	21	29.717	2.71	<.01
Screen	3	7.829	4.99	<.01
Covariate	1	3.474	6.65	.01
Error	62	32.405		

Multiple Comparisons For Screen Effect:

	Open	1-mm	2-mm	3-mm
Open	X	<.01	.11	.13
1-mm		X	.03	.03
2-mm			X	.98
3-mm				X

Table C-4. Two-way analysis of covariance for 1982 data on size class 2 (5-6 mm) naked gobies using port (left, right) and screen (open, 1-mm, and 2-mm) as main effects

Effect	DF	SS	F	P
Port	1	0.90	2.74	.12
Screen	2	0.19	0.29	.75
Covariate	1	5.26	16.02	
Error	18	5.91		

Table C-5. Two-way analysis of variance for 1982 data on size class 3 (7-8 mm) naked gobies using port (left, right) and screen size (open, 1-mm, and 2-mm) as main effects

Effect	DF	SS	F	P
Port	1	1.30	5.20	.03
Screen	2	5.25	10.53	<.01
Error	19	4.74		

Duncan's New Multiple Range Test For Screen Effect:

<u>Open Port</u>	<u>2-mm</u>	<u>1-mm</u>
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Table C-6. Two-way analysis of variance for 1983 data on size class 3 (7-8 mm) naked gobies using date-port as a blocking factor and screen size (open port, 1-mm, 2-mm and 3-mm) as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	25.980	2.53	<.01
Screen	3	44.658	30.46	<.01
Error	63	30.788		

Duncan's New Multiple Range Test For Screen Effect:

Open Port

3-mm   2-mm

1-mm

Table C-7. Two-way analysis of variance for 1982 data on size class 4 ( $\geq 9$  mm) naked gobies using port (left, right) and screen size (open port, 1-mm, and 2-mm) as main effects

Effect	DF	SS	F	P
Port	1	1.41	3.46	.08
Screen	2	13.21	16.25	<.01
Error	19	7.72		

Duncan's New Multiple Range Test For Screen Effect:

<u>Open Port</u>	<u>2-mm</u>	<u>1-mm</u>
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APPENDIX D

ANALYSIS OF VARIANCE TABLES FOR  
THE EFFECT OF THROUGH-SLOT VELOCITY/SCREEN  
DIAMETER ON BAY ANCHOVY ENTRAINMENT

Table D-1. Two-way analysis of variance for bay anchovy eggs using date-port as a blocking factor and screen diameter and through-slot velocity as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	308.07	1.20	.28
Velocity	3	44.44	1.21	.31
Error	63	770.15		

Table D-2. Two-way analysis of variance for bay anchovy size class 1 ( $\leq 4$  mm) using date-port as a blocking factor and through-slot velocity and screen diameter as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	72.52	3.49	<.01
Velocity	3	1.56	0.53	.67
Error	63	62.34		

Table D-3. Two-way analysis of variance for bay anchovy size class 2 (5-7 mm) using date-port as a blocking factor and through-slot velocity and screen diameter as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	63.39	6.89	<.01
Velocity	3	1.67	1.27	.29
Error	63	27.60		

Table D-4. Two-way analysis of covariance for bay anchovy size class 3 (8-10 mm) using date-port as a blocking factor and through-slot velocity and screen diameter as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	10.59	1.70	.05
Velocity	3	1.06	1.19	.32
Covariate	1	1.14	3.83	.05
Error	62	18.44		

Table D-5. Two-way analysis of variance for bay anchovy size class 4 (11-4 mm) using date-port as a blocking factor and through-slot velocity and screen diameter as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	0.64	0.87	.63
Velocity	3	0.23	2.23	.09
Error	63	2.21		

APPENDIX E

ANALYSIS OF VARIANCE TABLES FOR  
THE EFFECT OF THROUGH-SLOT VELOCITY AND SCREEN  
DIAMETER ON NAKED GORY ENTRAINMENT

Table E-1. Two-way analysis of covariance for size class 1 (<4 mm) naked goby using date-port as a blocking factor, screen diameter and through-slot velocity as the main effect, and canal density as the covariate

Effect	DF	SS	F	P
Blocking Factor	21	23.88	3.41	<.01
Velocity	3	3.35	3.35	.02
Covariate	1	6.87	20.56	<.01
Error	62	20.08		

Multiple Comparisons For Main Effect:

	SL	SH	LL	LH
Log Means				
SL - 1.19	X	.03	.83	.02
SH - 0.79		X	.04	.93
LL - 1.15			X	.03
LH - 0.78				X

SL - Small Screen/Low Pump Speed  
 SH - Small Screen/High Pump Speed  
 LL - Large Screen/Low Pump Speed  
 LH - Large Screen/High Pump Speed

Table E-2. Two-way analysis of covariance for naked goby size class 2 (5-6 mm) data using date-port as a blocking factor, through-screen slot velocity and screen diameter as the main effect, and canal density as the covariate

Effect	DF	SS	F	P
Blocking Factor	21	32.54	1.76	.04
Velocity	3	7.63	2.89	.04
Covariate	1	7.76	8.81	<.01
Error	62	54.63		

Multiple Comparisons For Main Effect:

	SL	SH	LL	LH
Log Means				
SL - 2.92	X	.12	.23	.46
SH - 2.47		X	<.01	.39
LL - 3.27			X	.05
LH - 2.71				X

SL - Small Screen/Low Pump Speed  
 SH - Small Screen/High Pump Speed  
 LL - Large Screen/Low Pump Speed  
 LH - Large Screen/High Pump Speed

Table E-3. Two-way analysis of variance for size class 3 (7-8 mm) naked goby data using date-port as a blocking factor and screen diameter and through-slot velocity as the main effect

Effect	DF	SS	F	P
Blocking Factor	21	21.36	1.30	.21
Velocity	3	21.00	8.93	<.01
Error	63	49.41		

Duncan's New Multiple Range Test For Main Effect:

<u>Small Screen</u> High Speed	<u>Large Screen</u> High Speed	<u>Large Screen</u> Low Speed	<u>Small Screen</u> Low Speed
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Table E-4. Two-way analysis of variance for size class 4 ( $> 9$  mm) naked goby data using date-port as a blocking factor, and screen diameter and through-slot velocity as the main effects

Effect	DF	SS	F	P
Blocking Factor	21	16.53	1.58	.08
Velocity	3	6.84	4.58	<.01
Error	63	31.35		

Duncan's New Multiple Range Test For Main Effect:

Small Screen  
High Speed

Large Screen  
High Speed

Large Screen  
Low Speed

Small Screen  
Low Speed

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